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GEOLOGIC INVESTIGATION OF
EXPERIMENTAL DRAINAGE BASINS 7 - 14,
BEAVER CREEK WATERSHED
COCONINO COUNTY, ARIZONA

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EXPERIMENTAL DRAINAGE BASINS 7 - 14,
BEAVER CREEK WATERSHED
COCONINO COUNTY, ARIZONA

by

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A cooperative project by the Rocky Mountain Forest and Range
Experiment Station, Northern Arizona University,
and the Museum of Northern Arizona,
Flagstaff, Arizona.

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INTRODUCTION

This report is the second resulting from geologic investigation of portions of the Beaver Creek watershed area conducted in collaboration with the Rocky Mountain Forest and Range Experiment Station. The first geologic study, involving watersheds 1 through 6, was reported by Rush (1965). These investigations are part of the long range watershed inventory being made on Beaver Creek by the Experiment Station. Financial and logistical support for this study was provided jointly by the Forest Service, Northern Arizona University, and the Museum of Northern Arizona. The Astrogeology Branch of the U. S. Geological Survey made available their facilities for duplicating maps and cross-sections.

LOCATION

The area of study is situated in southeastern Coconino County between Apache Maid Mountain and Brady Canyon on the south and Fain Mountain on the north and is in the general area east, northeast and southeast of Stoneman Lake (Fig. 1). The area is bounded approximately by latitudes 34°34' and 34°37' north and longitude 111°27' and 111°32' west, and is mostly within Township 16 north range 8 east, a small portion being in Township 17 north range 8 east and 9 east.

The area of specific interest is that covered by eight contiguous experimental watersheds--numbers 7 through 14--within the Beaver Creek watersheds which is part of the Verde River System. Individual watersheds range in size from less than ½ square mile for number 11 to more than three square miles for numbers 7 and 8. The total mapped area including some area adjacent to the actual watershed boundaries is approximately 40 square miles.

The watersheds together occupy portions of the following topographic quadrangles: Camp Verde 1 SE and 4 NE and Chaves Pass 2 SW and 3 NW. The range in elevation is from 6400 feet above sea level at the mouth of watershed 11 to 7936 feet at the summit of Jones Mountain on the east boundary of watershed 7. The maximum relief is thus about 1600 feet although it does not exceed 1400 feet in any one watershed. The U.S. Forest Service classification maps place these watersheds in the Ponderosa Pine Zone.

Physiographically the upper Beaver Creek draiage system is within the Grand Canyon region of the Colorado Plateau or Plateau Province of Arizona (Wilson. 1962, p. 97) and in a tectonic region designated by Kelly and Clinton (1960) as the Mogollon Slope. Twenter and Metzger (1963) recognize this area as part of the Mogollon Rim which marks the southern edge of the Colorado Plateau. Colton (1950) designated this area geologically as the Mormon Mountain volcanic field.

PURPOSE AND SCOPE

The general objective of this study is to describe and interpret geologic features within the watershed region that might effect runoff and sediment. The geologic studies include:

1. Preparation of a geologic map illustrating distribution of rock types and units.
2. Analysis and description of the stratigraphic succession exposed in this area.
3. Analysis of structural features.
4. Detailed petrographic analysis with the aid of thin sections.
5. Description and analysis of the development of geomorphic features.

Geologic features observed in the field, including distribution of rock types, structural, and geomorphic features, were plotted on aerial photographs (scale 1:20,000) and transferred to a topographic base of approximately the same scale by inspection. Areas adjacent to that covered by the designated watersheds were also examined where pertinent to an understanding of the regional geology and some of the data from these areas are incorporated in this report and on the geologic map.

The stratigraphic section, including both sedimentary and volcanic rocks, was measured with the aid of a steel tape and brunton compass. Petrographic examination was done by hand lens and petrographic microscope.

PREVIOUS WORK

The geology of the upper Beaver Creek area has been treated only briefly in some regional studies but no detailed work had been done prior to these watershed investigations. A summary of data published in adjacent areas is contained in the New Mexico Geological Society Guidebook, Thirteenth Annual Field Conference, Mogollon Rim Region (1962). Included in the Guidebook are short reports on upper Paleozoic rocks, Cenozoic sediments, Tertiary volcanics, and ground water in and around the Verde Valley. Twenter and Metzger, (1963) reported on the general geology and the ground water system of the Verde Valley which includes the Beaver Creek drainage as part of the ground water basin.

The city of Flagstaff derives a part of its water supply from wells near Lake Mary and Woody Mountain, which are a few miles north of the Beaver Creek area. Akers (1962) published a short summary of the geology of these areas. He disclosed the existence of a northwest-southeast trending faulted anticline, and showed that the surface water gradients are to the sotuhwest and to the northeast away from the anticlinal crest.

Cooley (1960) published some preliminary work on the volcanics of this region as part of a physiographic map on which the Beaver Creek area appears at the southern edge.

The monumental work on the volcanic field around the San Francisco Peaks was done by Robinson (1913). Although Robinson did not extend his exploration as far south as the Beaver Creek drainage, his work forms the basis for classifying volcanic events in surrounding areas. Colton (1950) modified the classification system of Robinson by using the degree of weathering of individual lava flows in the Flagstaff area. He also published some short notes (1957, 1964) relating to the volcanic geology of Stoneman Lake which is included in the area of this report.

STRATIGRAPHY

General Statement.--The rocks exposed in the upper Beaver Creek area are late Paleozoic sedimentary beds and volcanic rocks of Cenozoic age. A generalized section of the rocks exposed in the Verde Valley and Mogollon Rim region of Arizona is given below as modified from Twenter and Metzger (1963):

Table 1. Generalized section of rocks in Verde Valley, Arizona after Twenter and Metzger (1963)

Era	System	Series	Group	Formation	Thickness (feet)	Lithologic characteristics
Cenozoic	Quaternary	Pleistocene and Recent		Streamwash	0-30+	Terrace deposits and stream deposits Unconformity
		Pleistocene		Gravel	0-70	Gravel and minor amounts of sand, silt, and clay; fragments derived from adjacent bedrock. Unconformity
			Volcanic rocks		0-300	Rhyolitic lava, rhyodacite, and a few beds of tuffaceous sediments. Unconformity
	Tertiary or Quaternary	Pliocene or Pleistocene(9)	Verde Formation		1,800+	Diverse lithology resulting from facies changes of sediments deposited in a closed or partly closed basin. A thick limestone facies is adjacent to the Verde River (thick facies); away from the thick facies the rocks change rapidly to interbedded limestone and clastic material. Several thin basaltic flows are intercalated in the lakebeds. Unconformity
	Tertiary	Miocene(?) and Pliocene	Volcanic rocks		0-1,000+	Basaltic lava, dikes, cinder cones, and volcanic sedimentary rocks. Fragments in the sedimentary rocks are chiefly volcanic; a few beds are composed mostly of fragments of Precambrian and Paleozoic rocks. Unconformity
		Miocene(?)	Sedimentary rocks		0-1,000+	Conglomerate, gravel, very coarse to very fine grained sandstone, siltstone, bentonitic clay, marl, and some limestone. Precambrian and Paleozoic rock fragments predominate in most exposures.

Table 1. Generalized section of rocks in Verde Valley, Arizona after Twenter and Metzger (1963)--Continued

Era	System	Series	Group	Formation	Thickness (feet)	Lithologic characteristics
Mesozoic	Triassic			Moenkopi Formation	0-100+	Siltstone, fine grained sandstone and shale
						Unconformity
Paleozoic	Permian		Aubrey Group	Kaibab Limestone	300±	Limestone or dolomitic limestone containing nodules and thin beds of chert. Some calcareous sandstone, especially in the northwestern part of the area.
				Toroweap Formation	150-350	In most of the valley the formation is very fine grained to fine grained sandstone. In the Sycamore Creek area a basal sandstone is overlain by sandstone and sandy limestone and, in turn, by sandstone, siltstone, and shale.
				Coconino Sandstone	400-650	Sandstone composed of very fine grained to fine grained rounded to subrounded grains of quartz. Conspicuous large-scale crossbedding.
	Pennsylvanian and Permian			Supai Formation	1,500-1,600±	Lower member, about 600 ft. thick, is composed of thin beds of sandstone, mudstone, limestone, and dolomite. Middle member, about 275 ft. thick, is composed of thin bedded dolomitic intraformational conglomerate, mudstone, limestone, siltstone, and sandstone. Upper member, more than 650 ft. thick, is composed of sandstone and siltstone.
						Unconformity

Table 1. Generalized section of rocks in Verde Valley, Arizona after Twenter and Metzger (1963)--Continued

Mississippian		Redwall Limestone		235-286	Unconformity Coarsely crystalline cherty limestone. Some beds contain crinoids, brachiopods, corals, and other fossils.
Devonian	Middle(?) and Upper Devonian	Martin Limestone		450-500	Unconformity Dolomite and dolomitic limestone. Contains thin beds of mudstone, shale, and sandstone. Some beds are very fossiliferous. Contact with the Tapeats(?) appears gradational.
Cambrian	Lower and Middle Cambrian	Tonto Group	Tapeats(?) Sandstone	0-100±	Upper beds of siltstone and limy or dolomitic mudstone grade downward into beds of conglomerate and coarse-grained sandstone.
Precambrian					Unconformity Intrusive rocks, chiefly diorite and quartz porphyry.
	Yavapai	Ash Creek Group		20,000±	Basaltic, rhyolitic, andesitic, and dacitic flows; rhyolitic and volcanic breccia; basaltic and andesitic agglomerate; and tuffaceous sedimentary rocks. All rocks are metamorphosed.

No Paleozoic sediments crop out within the confines of the watersheds studied but immediately to the south of watershed 11 is an outcrop of the Kaibab Formation about ½ square mile in area (see Plate 1). Moreover, numerous inclusions of chert and limestone from the Kaibab Formation and quartz sandstone from the Coconino Sandstone occur in the volcanics throughout the watershed areas, indicating that the upper Paleozoic strata are present beneath the volcanic cover.

Plate 4 presents a composite section of the rocks exposed in the watershed areas and in the upper part of Wet Beaver Creek Canyon. The stratigraphic sequence displayed in the walls of upper Wet Beaver Creek Canyon is particularly instructive because it provides the best third dimensional or vertical view of the rocks believed to be present beneath the watershed areas. At a point about three miles south of Apache Maid Mountain a 900-foot section is exposed including 250 feet of Paleozoic strata and more than 600 feet of volcanics.

Older Paleozoics.--Although only the upper part of the Paleozoic sequence crops out, strata of middle and early Paleozoic age, as indicated in Table 1, are probably present in subcrop beneath the mapped area. Wells drilled south of Flagstaff, northeast of Mormon Lake, and in the Verde Valley have penetrated a thick redbed sequence of the Supai Formation and in some places also the Redwall Limestone, and Martin Formation beneath (Scurlock, 1966).[1] A thin sandstone section, recognized as the Tapeats Sandstone of Cambrian age, occurs beneath the Martin Formation and above the crystalline Precambrian basement rocks near Jerome and in the Pine Payson area to the southeast. The Tapeats is presumably present beneath the watershed areas as well.

[1] Also well log data filed at the Museum of Northern Arizona

Coconino Sandstone.--The lowermost unit at the Wet Beaver Creek section is a buff colored sandstone which forms an inner gorge about 60 to 70 feet deep. The sandstone consists almost entirely of rounded, well sorted quartz grains of medium sand size (1/2-1/4mm.) and is both porous and permeable. The most striking feature is the large scale wedge shaped cross-bedding displayed throughout the entire thickness exposed. The cross-bedding units have dips up to 27 degrees and dip generally to the southwest. The nature and size of the crossbeds suggest a wind blown sand deposit typical of the Coconino Sandstone.

A few of the cross-bedding sets have level tops and bottoms similar to those described by McKee (1938) for the sandy eastern phase of the Toroweap Formation which overlies the Coconino in the Oak Creek Canyon area. However, the cross-beds in Wet Beaver Creek are on such a large scale and are so predominantly wedge-shaped Coconino type that recognition of the Toroweap here does not seem justified. Whatever name be most appropriate, the exposed beds are representative of a more than 500-foot sandstone section present beneath the Kaibab Formation in this area. Similar cross-bedded sandstones form at least 400 feet of Canyon wall in West Clear Creek Canyon, eight miles south of the Wet Beaver Creek Section. The base of the sandstone is not exposed in either locality. In Oak Creek Canyon, 35 miles to the northwest, the combined Toroweap-Coconino Sandstone section is more than 600 feet thick.

Kaibab Formation.--Above the Coconino is a 180-foot sequence of cherty and in part sandy and silty limestone of the Kaibab Formation. The Kaibab includes some beds composed entirely of yellowish gray chert which is irregularly fractured. Irregular nodules and stringers of chert are present throughout much of the limestone strata. The Kaibab is mostly resistant and forms a series of nearly vertical ledges and cliffs in which horizontal breaks due to bedding or parting are abundant. Numerous vertical joints occur in the Kaibab and locally some channels and caverns, developed by ground water solution along fractures, were observed.

Fossils are abundantly present but poorly preserved in the Kaibab. The few productid brachipod forms recognized are identical to those described elsewhere in the formation.

The exposed Kaibab is considered equivalent to the Beta Member of McKee (1938). The Alpha Member is apparently absent due to erosion of the upper Kaibab before the overlying volcanics accumulated.

Mesozoic Strata.--Mesozoic beds of Triassic through Cretaceous age probably once covered this region but were almost entirely removed by erosion before volcanism occurred. Isolated patches of Triassic redbeds of the Moenkopi Formation occur on the edge of Oak Creek Canyon to the northwest and in the Willow Valley area about 10 miles to the southeast of the study area.

CENOZOIC VOLCANICS

General Statement.--Volcanic rocks blanket the entire area of the eight watersheds studied and are everywhere exposed except where covered by mantle, alluvium, or lake beds. The thickness of the volcanics varies from near zero at the south end of watershed 11 to an estimated 1000 feet or more in the vicinity of some of the cinder cones. The average thickness is estimated to be approximately 450 feet, based upon the projected position of the erosion surface on the Kaibab Formation upon which the volcanics were deposited.

Three or possibly four major stages of volcanic activity can be recognized from the volcanics exposed in the watershed areas and in upper Wet Beaver Creek as follows:

Stage I	Bedded tuffs and tuff breccias
Stage II	Older lava flows, mostly olivine basalts
Stage III	Younger lava flows of basalt and andesite traceable to existing vents.
Stage IV	Cinder cones and some small thin lava flows. These may have been in part contemporaneous with the younger lavas of stage III.

Stage I.-Tuffaceous beds.--The first stage is represented by several hundred feet of tuffaceous sediments and volcanic breccia exposed in Wet Beaver Creek. Although only 100 feet of tuff was recorded in the measured section the tuff is considerably thicker where it is more completely preserved in down-dropped fault blocks.(Plate 5). The tuff is composed of light colored fragments of volcanic glass, feldspar and quartz crystals, and some volcanic rock fragments, and is primarily a crystal vitric tuff. Most of the grains are coarse sand size (1-2mm.) although some pebble size as well as fine sand and silt size fragments occur. A few thin units of tuff breccia--ash, cinders, and larger angular blocks of pyroclastic debris--also occur in the tuffaceous sequence. The tuff is well bedded and weakly cemented and on the whole quite porous and permeable (Plate 6). It is only slightly resistant to erosion and forms slopes between the cliffs of more resistant Kaibab Limestone below and the massive lavas above.

Tuffs of the first stage crop out only in Wet Beaver Creek Canyon. No tuffaceous sediments were recognized where the stage II lavas overlap the Kaibab Formation south of watershed 11 but they may well be present locally beneath these older lavas in some of the watershed areas. Similar younger tuffaceous beds do occur between the stage II lava flows. One 20-foot sequence is exposed locally to the north and east of Sugarloaf Mountain in watershed 7.

In stratigraphic position, beneath the oldest basalts, and in lithologic similarity, the tuff beds resemble those of the Hickey Formation as described by Sabels (1962) in the Camp Verde, Sedona, and Dry Beaver Creek areas. A radiometric age date of 14 million years (Late Miocene) was reported by Sabels for the tuffs in the Hickey Formation. No precise correlation of the tuffs at Wet Beaver Creek is possible until radiometric dates or additional compositional and stratigraphic data are obtained.

Stage II Older basalts.--The greatest bulk of volcanic material extruded in this area came out as a series of fluid, relatively horizontal basalt flows. These flows are present throughout the mapped area and have been partly dissected by most of the stream valleys. They form almost the entire floor of watersheds 11 and 12. They crop out over more than half of watersheds 7, 8, 9, 13, and 14, and in less than half of watershed 10. Where vertically displayed the older basalts exhibit columnar jointing which may extend the entire thickness of the flows but does not continue into the flows above or below. Rather, each flow has its own system of columnar joints (Plate 8). In some outcrops flow lines, accentuated by fracturing or sheeting due to weathering, are visible. Lava tunnels were observed near the base of two of the massive flows (Plate 9). Individual flows cannot be readily distinguished by lithologic differences, except in one example, because nearly all are of uniform olivine basalt composition and in hand specimen exhibit similar flow orientation of feldspar crystals. Separate flows can be recognized by superposition where exposed in canyon walls as at Brady Canyon, along drainage channels in watersheds 7-10, and in Wet Beaver Creek Canyon where at least six distinct flows are visible (Plate 7). At the latter locality the flows are separated by 1 to 15 foot units of tuff or breccia.

At Stoneman Lake three superposed older basalt flows can be distinguished lithologically--a lower olivine basalt, a middle labradorite basalt porphyry having distinct light gray feldspar phenocrysts and 80 to 100 feet thick, and an upper olivine basalt more than 100 feet thick. In addition a fouth unit, a blocky weathering, fine grained olivine basalt (belonging to the stage III or younger basalts) is present around the northeastern part of the rim. The labradorite basalt is also recognized in outcrop about a mile southwest of Stoneman Lake and in the lower drainage channels of watersheds 8 and 9, indicating that it was an extensive flow covering at least 10 square miles and perhaps much more.

These older basalt flows cannot be traced to any specific vents but must have arisen from a series of existing fractures from which they were extruded as quiet fissure eruptions to flow generally southwestward down the slope of the ancestral Mogollon Rim. On gently sloping surfaces within the watershed areas the weathered and eroded fronts of some flows are expressed topographically as low cliffs with some rubble at the base as in the lower part of watershed 11. The original flow fronts and flow surfaces have been destroyed by weathering and erosion and further modified by soil cover which locally is several feet deep.

Younger basalts and cinder cones.--The younger basalts of stage III are those which can be associated with an existing vent, usually marked by a cinder cone, and which clearly overlie the older or stage II basalts. These are mostly olivine or augite basalts which exhibit a small scale, irregular or blocky appearance both on weathered and freshly broken surfaces due to numerous incipient fractures. In hand specimen they also seem to lack marked flow orientation of feldspars so common in the older basalts.

One major flow of andesite, containing large slender phenocrysts of hornblende, covers parts of watersheds 7, 10 and 13. The andesite flow originated from a point marked by a small summit at the junction of the above three watershed boundaries. Other major vents from which younger basalt flows emanated are marked by Fain Mountain and the associated cones at the north edge of watershed 9, Lake Mountain north of Stoneman Lake, Jones Mountain on the east side of watershed 7, Bill Back Butte on the northeast side of watershed 14, and [illegible] the middle of watershed 7. Numerous small unnamed cones

14, and Sugar Loaf in the middle of watershed 7. Numerous small unnamed cones also mark vents for local flows as indicated on Plate 1.

The younger flows appear to have been somewhat stiffer and more viscous than the older basalts. None have been observed to extend more than two miles from their vent and some have formed surfaces having slopes of 10-25 degrees. In general the flow boundaries, though somewhat weathered, are clearly visible on aerial photographs and are topographically expressed where not obscured by vegetation. On a few of the younger flow surfaces squeeze-ups and scoracious blocks are partially preserved, indicating that weathering and erosion have not proceeded very far.

Practically every summit, of which there are about 30 in the mapped area, marks a volcanic vent from which lava, cinders, or both, were extruded. The cones thus formed are mostly composite in that they consist of both lava and pyroclastic debris such as ash, cinders, blocks and bombs, with pyroclastic material predominating. On the geologic map the lithnology of the cones is indicated according to the predominant rock type observed at the surface. The cinders below the surface are slightly to well indurated by cementation with calcite precipitated from water percolating through the loose fragments. In spite of the cementation the cinder deposits appear to be both porous and permeable.

Although no precise dates are available the younger flows and cinder cones are considered to be Late Pleistocene in age on the basis of the degree of preservation. It is likely that some of the younger flows were extruded simultaneously with the building of the associated cinder cones, as has been observed in modern eruptions.

Intrusive bodies.--Numerous small shallow intrusive bodies--dikes and plugs--are associated with the cinder cones. These are all of basaltic composition and represent lava which congealed in the conduit before reaching the surface as a flow. At the summit of most cinder cones is a basalt plug or volcanic neck which stands up as a resistant body of solidified lava occupying the throat of the vent.

A large plug of labradorite basalt porphyry is prominently displayed on the north wall of Stoneman Lake (Plate 10). It is about 500 feet across and has a flat top nearly coincident with the level of the lake rim but does not correspond lithologically with the rim rock immediately behind it to the north and northeast.

Lake Mountain and Sugar Loaf exhibit a distinct radiating pattern of dikes--vertical sheets of lava--which solidified in fractures before reaching the surface. Some of these dikes now stand out as vertical ribs five or ten feet above the eroded surface of the cinders through which they were extruded. A number of near vertical dikes are exposed in the walls of West Clear Creek and Wet Beaver Creek, with an exposed vertical extent greater than 500 feet (Plate 5). The dikes form local barriers to the movement of both surface and ground water and may also provide a conduit down the fracture they occupy along which water may descend to the regional water table.

PETROGRAPHY OF VOLCANIC ROCKS

General Statement.--The volcanic rocks of the Beaver Creek watersheds can be classified into two major groups. The major portion of the rocks belong to the group termed plateau basalts because of their occurrences in the great volcanic plateaus of the world; ie, the Deccan Plateau and the Columbia Plateau. The second volcanic group is composed of one flow covering approximately one square mile in area and consisting of an intermediate volcanic rock classified as an andesite. The volcanic rock types have a variety of characteristics which can be presented in textural and structural terms.

Texture.--The volcanic rocks of the Beaver Creek Watershed are typical volcanic rocks with a variety of textural features. Grain size variation is by far the most obvious textural feature exhibited. The rocks vary from holocrystalline to holohyaline in texture, with hypocrystalline textures predominating. Most of the rocks examined are hypocrystalline with glass volumes of 5-20% and crystal volumes of 80-95%. A few are holocrystalline, 100% crystalline, while a lesser number are holohyaline, 100% glass. The feature of crystallinity is a direct indication of cooling rate and composition. The more rapid the cooling rate the greater the glass content. Most rocks show porphyritic textures with one or more of the minerals being much greater in size than the remainder. Grain size of the groundmass of the basalts varies from very fine (.02-.06 mm) to fine grained (.06-.1), with most specimens showing distinct phenocrysts. This indicates that the melts (lavas) exited at the surface as partially crystallized materials.

The most distinctive feature of the groundmass of the basalts is the presence of lath-shaped feldspar crystals intermixed with a variety of other materials. Many of the specimens show flow lineation of the plagioclase feldspar laths, and others show a flow banding of the mineral constituents of the lava, along with the flow lineation of the plagioclase. A number of the rock specimens showed completely random orientation of the plagioclase. The other constituents consisting of augite, magnetite, and glass, are found as interstitial grains and masses surrounding the feldspars in the groundmass.

The phenocrysts consist of a single mineral, two minerals or three minerals. Table II indicates the classification of each sample. The minerals represented as phenocrysts are olivine, augite, labradorite, and hornblende. The phenocrysts are striking features of the rocks and tend in many specimens to give a speckled coloration to the hand specimens.

One group of volcanic rocks found in and around Stoneman Lake contains abundant calcic plagioclases which are nearly euhedral evidencing crystallization from a melt with sufficient time and room for crystall growth. A few crystals show embayments indicating reaction with the changing chemical environment of the magma, however most are sharp and fresh. The presence of the feldspar phenocrysts in these rocks makes them readily mappable as a unit in the field.

The olivine which is the most abundant phenocryst of the volcanics is usually present in euhedral grains with border zones which show various grades of corrosion and alteration. With few exceptions the olivines are enclosed by rinds of iddingsite, and in some cases the entire mineral

Table II

Sample No.	Phenocrysts	Horn.	Oliv.	Aug.	And.	Lab.	Mag.	Glass
W7-1	Olivine		5%	35%		40%	5%	14%
W7-2	Olivine		20%	35%		40%	5%	
W7-3	Olivine		30%	25%		35%	7%	3%
W7-4	Oliv. & Aug.		10%	45%		30%	4%	11%
W7-5	Lamp. & Aug.	15%		45%		30%	5%	5%
W7-6	Olivine		15%	40%		35%	5%	5%
W7-7	Olivine		15%	35%		25%	10%	15%
W7-8	Lamp. & Aug.	24%		30%		25%		20%
W7-9	Lamp. & Feldspar	20%				50%	5%	25%
W7-10	Lamprobalite	2%		3%		40%	5%	50%
W7-11	Labradorite		1%			75%	2%	22%
W7-12	Labradorite		2%			50%	3%	45%
W7-13	Olivine		25%	30%		35%	3%	7%
W7-14	Olivine		25%	30%		30%	5%	10%
W7-15	Olivine		15%	5%		60%		20%
W7-16	Olivine		20%	30%		25%	10%	15%
W7-17	Oliv. & Lab.		25%	15%		43%		17%
W7-18	Olivine		50%			10%		40%
W7-19	Oliv. & Aug.		25%	35%		35%	5%	
W7-20	Oliv. & Aug.		15%	35%		42%	3%	5%
W7-21			1%	1%		75%	3%	20%
W7-22	Lamprobalite	3%				45%	1%	50%
W7-23	Aug. & Oliv.		5%	50%		40%	2%	3%
W7-24	Oliv. & Aug.		25%	40%		25%	5%	5%
W7-25	Olivine		10%	35%		30%	10%	15%
W8-1	Olivine		30%			50%	5%	15%
W8-2	Olivine		10%	35%		40%	5%	10%
W8-3	Olivine		10%	30%		50%	10%	
W8-4	Aug. & Oliv.		5%	38%	2%	55%		
W8-5	Lab. & Oliv.		15%	30%		50% (25% Ph)	5%	
W8-6	Lab. & Oliv.		35%	(10% Ph.)		55% (15% Ph)	10%	
W8-7	Olivine		20%	20%		40%	5%	15%
W8-8	Lamprobalite	25%		15%		40%	15%	5%
W8-9	Lamprobalite	25%		30%		30%		15%
W8-9	Lamp. & Oliv.	5%	10%	5%		40%	2%	18%
W8-10	Olivine		25%	25%		30%	10%	10%
W8-11	Oliv. & Lamp.	5%	12%	30%		40%	10%	3%
W8-12	Olivine		20%	30%		30%	3%	17%
W9-1	Olivine		15%	25%		35%	5%	20%
W9-2		4%				10%		85% (50% hematite)
W9-3	Oliv. & Horn.	25%	20%			20%		35%
W9-4	Augite			35%		22%	3%	40%
W9-5	Hornblende	20%				40%		40%
W9-6			25%			60%	3%	12%

Sample No.	Phenocrysts	Horn.	Oliv.	Aug.	And.	Lab.	Mag.	Glass
W9-7			30%			27%	3%	40%
W9-8			25%	(5% Ph.)	20%	25%	5%	25%
W9-9			49%	50%			1%	
W10-1	Lamprobalite	20%			50%			30%
W10-2	Olivine		15%	30%		50%	5%	
W10-3	Olivine		20%	30%		45%	5%	
W10-4	Olivine		20%	20%		58%	2%	
W10-5	Lamprobalite	5%		1%	60%			35%
W10-6	Lamprobalite	5%			55%		5%	35%
W10-7	Lamprobalite	3%		1%	60%			35%
W10-8		2%			60%			38%
W10-9		5%			70%		25%	
W10-10	Olivine		10%	15%		65%	2%	8%
W11-1	Lamprobalite	20%			40%			40%
W11-2	Olivine		10%	30%		50%		10%
W12-2	Augite & Oliv.		15%	20%		50%	5%	10%
W12-2	Olivine		20%	15%		50%	7%	8%
W12-3	Augite & Oliv.		5%	45%		40%	5%	5%
W12-4	Aug.,Oliv.,Lamp.	15%	5%	25%		40%	10%	5%
W12-6	Augite & Oliv.		15%	35%		40%	5%	5%
W12-6	Augite			25%		50%	1%	24%
W13-1	Lamp. & Aug.	10%		10%		30%		50%
W13-2	Augite			20%		55%	1%	24%
W13-3	Lamp.,Aug.,Oliv.	10%	5%	15%		60%	5%	5%
W13-4	Lamp. & Aug.	15%	3%	10%		55%	10%	7%
W13-5	Olivine		20%	20%		40%	10%	10%
W13-6	Oliv. & Aug.		15%	15%		45%	10%	15%
W13-7	Olivine		10%	40%		40%	5%	5%
W13-8	Olivine		15%	45%		30%	5%	5%
W13-9	Oliv. & Aug.		15%	45%		32%	3%	5%
W13-10	Olivine		15%	40%		35%	5%	5%
W13-11	Olivine		5%	35%		40%	10%	15%
W13-12	Olivine		10%	25%		53%	2%	10%
W13-13	Olivine		15%	20%		55%	5%	5%
W13-14	Olivine		10%	20%		60%	5%	5%
W13-15	Olivine		5%	15%		75%	5%	
W13-16	Olivine		15%	10%		60%	5%	10%
W14-1	Olivine		15%	15%		30%	5%	35%
W14-2	Lamprobalite	10%		5%		10%	5%	70%
W14-3	Oliv. & Aug.		15%	15%		30%	10%	30%
W14-4	Augite			50%		45%	5%	
W14-5			25%	40%		25%	5%	5%
W14-6	Olivine		40%	15%		30%	5%	10%
W14-7			35%	15%		20%	5%	25%

Sample No.	Phenocrysts	Horn.	Oliv.	Aug.	And.	Lab.	Mag.	Glass
W14-8	Olivine		45%	20%		20%	5%	10%
W14-9	Olivine		20%	10%		50%	5%	15%
W14-10	Olivine		15%	30%		40%	5%	10%
W14-11	Olivine		25%	35%		25%	5%	10%
W14-12	Lamprobalite	15%		10%		55%	10%	10%
W14-13	Olivine		25%	15%		35%	10%	15%
W14-14	Olivine		10%	15%		60%	5%	10%
W14-15	Olivine		20%	20%		20%	5%	35%
W14-16	Olivine & Aug.		5%	25%		65%	5%	
W14-18	Olivine		20%	35%		30%	5%	10%
SL 1	Lamprobalite	5%	5%	20%		15%	5%	50%
SL 2	Labradorite		5%	35%		50%	5%	5%
SL 3	Labradorite		5%	15%		65%(15%Ph)	10%	5%
SL 4	Labrador. & Oliv.		10%	40%		35%(15%Ph)	5%	10%
SL 5	Labradorite		5%	35%		45%(15%Ph)	5%	10%
A Hill 773B	Augite			30%		5%		60%
A Hill 773B	Lamprobalite	20%		5%				75%
B Hill B-1	Lamprobalite	20%				70%	5%	5%
B Hill B-2	Augite			35%		40%	5%	20%
B Hill #2	Augite			25%		60%		15%
C Hill C-1	Augite & Oliv.		10%	20%		55%	5%	10%
D Hill #1	Lamprobalite	20%		20%	50%			10%
E Hill #2	Olivine		20%	20%		30%	5%	25%
F Hill	Lamprobalite	20%				20%		60%
F Hill #3	Olivine		20%	10%		15%	10%	45%
G - 1	Olivine		20%	30%		40%	5%	5%
H - 1	Aug. & Lampro.	20%		25%		20%	5%	30%
K Hill #1	Olivine & Aug.		25%	25%		45%		5%
K Hill #2	Augite			20%		5%		75%
Lake Mtn.	Augite		5%	30%		60%	5%	10%
T - 1	Augite			5%				95%
8-66-23	Hornblende	5%	20%	5%		55%	5%	10%

has been converted into iddingsite. Augite is found as a rather abundant phenocryst in the rocks. It, however, is normally anhedral, and is frequently subophitic in relation to feldspar laths that penetrate into the pyroxene and sometimes are enclosed by it. In most cases the pyroxene is fresh, showing little or no evidence of alteration.

Hornblende is found as phenocrysts in a number of flows, and in all but one flow is the variety lamprobalite, commonly called basaltic hornblende. These phenocrysts of lamprobalite are commonly corroded and embayed by later solution in the magma; evidencing considerable change in the melt following the crystallization of the amphibole. Lamprobalite commonly shows considerable alteration particularly, near the borders where much of the crystal is replaced by magnetite and other dark oxides of iron and manganese.

In one small outcrop just east of watershed 14 is located a basaltic flow with small areal outcrop which contains hornblende. The largest crystals are up to 3/4 inch in diameter and over 1½ inches in length. Optical evidence indicates the mineral to be hornblende which is a rare mineral in volcanic rocks with basaltic composition.

Inclusions of various minerals are found in some of the lavas and these minerals may give the impression of their being phenocrysts. Most show intensive alteration and are evidently late stage inclusions which were torn from the walls of the vent and incorporated in the magma. The minerals observed were mainly the sodic feldspar, andesine, and quartz; however, one crystal of spinel was observed. Quartz grains where present are universally surrounded by reaction coronas. Most of the reaction rims are so fine grained that the minerals are not identifiable.

Petrographic Structure.--The volcanic rocks of the Beaver Creek watershed are characterized by petrographic structures which are common in most volcanic rocks. The structures vary from massive at the base of deep flows to vesicular at the top and pumiceous in the pyroclastics of the prominent hills of the watershed. Many of the older lavas show prominent flow banding which is discernable in the hand specimen.

Classification of Igneous Rocks.--The rocks of the Beaver Creek watershed are classified according to Johannsen's Classification (1937). Table III gives the classification of the samples and also the dominant phenocrysts. Most samples are porphyritic and have one or more conspicuous phenocrysts which are used in assigning names to the specimens.

As seen from the table the rocks are readily classified as basalts and andesites. The flow in watershed 10 is the only prominent rock that would not fit into the term plateau basalt, and is probably the product of late stage differentiation of the magma at depth beneath the area. Normal differentiation of basaltic magma produces rocks which are more acidic in nature. This late stage flow is represented by a lamprobalite andesite in watershed 10.

Table III

Sample No.	Phenocrysts	Classification
W7-1[1]	Olivine	Basalt
W7-2	Olivine	Porphyritic Olivine Basalt
W7-3	Olivine	Porphyritic Olivine Basalt
W7-4	Olivine & Augite	Porphyritic Olivine Augite Basalt
W7-5	Lamprobalite & Augite	Porphyritic Hornblende Basalt
W7-6	Olivine	Porphyritic Olivine Basalt
W7-7	Olivine	Porphyritic Olivine Basalt
W7-8	Lamprobalite & Augite	Porphyritic Hornblende Augite Basalt
W7-9	Lamprobalite & Feldspar	Porphyritic Hornblende Basalt
W7-10	Lamprobalite	Basalt
W7-11	Labradorite	Lucobasalt
W7-12	Labradorite	Lucobasalt
W7-13	Olivine	Porphyritic Olivine Basalt
W7-14	Olivine	Porphyritic Olivine Basalt
W7-15	Olivine	Olivine Basalt
W7-16	Olivine	Porphyritic Olivine Basalt
W7-17	Olivine & Labradorite	Olivine Basalt Porphyry
W7-18	Olivine	Olivine Basalt Porphyry
W7-19	Olivine & Augite	Porphyritic Olivine Basalt
W7-20	Olivine & Augite	Porphyritic Olivine Augite Basalt
W7-21		Basalt
W7-22	Lamprobalite	Basalt
W7-23	Augite & Olivine	Porphyritic Augite Basalt
W7-24	Olivine & Augite	Porphyritic Olivine Basalt
W7-25	Olivine	Olivine Basalt
W8-1	Olivine	Porphyritic Olivine Basalt
W8-2	Olivine	Porphyritic Olivine Basalt
W8-3	Olivine	Porphyritic Olivine Basalt
W8-4	Augite & Olivine	Basalt
W8-5	Labradorite & Olivine	Labradorite Basalt Porphyry
W8-6	Labradorite & Olivine	Labradorite Olivine Basalt Porphyry
W8-7	Olivine	Porphyritic Olivine Basalt
W8-8	Lamprobalite	Porphyritic Hornblende Basalt
W8-9	Lamprobalite	Porphyritic Hornblende Basalt
W8-9	Lamprobalite & Olivine	Porphyritic Hornblende Olivine Basalt
W8-10	Olivine	Porphyritic Olivine Basalt
W8-11	Olivine & Lamprobalite	Porphyritic Olivine Basalt
W8-12	Olivine	Porphyritic Olivine Basalt
W9-1	Olivine	Olivine Basalt Porphyry
W9-2		Igneous Vitrophyre
W9-3	Olivine, Hornblende	Hornblende Olivine Basalt Porphyry
W9-4	Augite	Porphyritic Augite Basalt
W9-5	Hornblende	Porphyritic Hornblende Basalt
W9-6		Olivine Basalt
W9-7		Olivine Basalt
W9-8		Porphyritic Labradorite Basalt
W9-9		Picrite

Sample No.	Phenocrysts	Classification
W10-1	Lamprobalite	Hornblende Andesite Porphyry
W10-2	Olivine	Porphyritic Olivine Basalt
W10-3	Olivine	Porphyritic Olivine Basalt
W10-4	Olivine	Porphyritic Olivine Basalt
W10-5	Lamprobalite	Porphyritic Hornblende Andesite
W10-6	Lamprobalite	Porphyritic Hornblende Andesite
W10-7	Lamprobalite	Porphyritic Hornblende Andesite
W10-8		Andesite
W10-9		Andesite
W10-10	Olivine	Porphyritic Olivine Basalt
W11-1	Lamprobalite	Hornblende Basalt
W11-2	Olivine	Porphyritic Olivine Basalt
W12-1	Augite & Olivine	Porphyritic Olivine Basalt
W12-2	Olivine	Porphyritic Olivine Basalt
W12-3	Augite & Olivine	Porphyritic Augite Olivine Basalt
W12-4	Augite & Olivine & Lampro.	Porphyritic Augite Hornblende Basalt
W12-5	Augite & Olivine	Porphyritic Augite Olivine Basalt
W12-6	Augite	Porphyritic Augite Basalt
W13-1	Lamprobalite & Augite	Porphyritic Hornblende Basalt
W13-2	Augite	Porphyritic Augite Basalt
W13-3	Lamprobalite, Augite & Olv.	Porphyritic Hornblende Basalt
W13-4	Lamprobalite & Augite	Porphyritic Hornblende Basalt
W13-5	Olivine	Porphyritic Olivine Basalt
W13-6	Olivine & Augite	Porphyritic Olivine Basalt
W13-7	Olivine	Porphyritic Olivine Basalt
W13-8	Olivine	Porphyritic Olivine Basalt
W13-9	Olivine & Augite	Porphyritic Olivine Augite Basalt
W13-10	Olivine	Porphyritic Olivine Basalt
W13-11	Olivine	Porphyritic Olivine Basalt
W13-12	Olivine	Olivine Basalt
W13-13	Olivine	Porphyritic Olivine Basalt
W13-14	Olivine	Porphyritic Olivine Basalt
W13-15	Olivine	Basalt
W13-16	Olivine	Porphyritic Olivine Basalt
W14-1	Olivine	Porphyritic Olivine Basalt
W14-2	Lamprobalite	Vitric Basalt
W14-3	Olivine & Augite	Basalt
W14-4	Augite	Porphyritic Augite Basalt
W14-5		Olivine Basalt
W14-6	Olivine	Olivine Basalt
W14-7		Olivine Basalt
W14-8	Olivine	Olivine Basalt
W14-9	Olivine	Olivine Basalt
W14-10	Olivine	Porphyritic Olivine Basalt

Sample No.	Phenocrysts	Classification
W14-11	Olivine	Porphyritic Olivine Basalt
W14-11	Olivine	Porphyritic Olivine Basalt
W14-12	Lamprobalite	Porphyritic Hornblende Basalt
W14-13	Olivine	Olivine Basalt
W14-14	Olivine	Olivine Basalt
W14-15	Olivine	Porphyritic Olivine Basalt
W14-16	Olivine & Augite	Augite Olivine Basalt
W14-18	Olivine	Olivine Basalt
SL 1[2]	Lamprobalite	Hornblende Olivine Basalt
SL 2	Labradorite	Labradorite Basalt Porphyry
SL 3	Labradorite	Labradorite Basalt Porphyry
SL 4	Labradorite & Olivine	Labradorite Basalt Porphyry
SL 5	Labradorite	Labradorite Basalt Porphyry
A Hill 773B[3]	Augite	Porphyritic Augite Basalt
A Hill 773B	Lamprobalite	Porphyritic Hornblende Basalt
B Hill B-1	Lamprobalite	Porphyritic Hornblende Basalt
B Hill B-2	Augite	Porphyritic Augite Basalt
B Hill #2	Augite	Porphyritic Augite Basalt
C Hill C-1	Augite & Olivine	Porphyritic Augite Olivine Basalt
D Hill #1	Lamprobalite	Porphyritic Hornblende Andesine
E Hill #2	Olivine	Porphyritic Olivine Basalt
F Hill	Lamprobalite	Porphyritic Hornblende Basalt
F Hill #3	Olivine	Porphyritic Olivine Basalt
G - 1	Olivine	Porphyritic Olivine Basalt
H - 1	Augite & Lamprobalite	Porphyritic Augite Hornblende Basalt
K Hill #1	Olivine & Augite	Olivine Basalt
K Hill #2	Augite	Porphyritic Augite Basalt
Lake Mtn.	Augite	Porphyritic Augite Basalt
T - 1	Augite	Augite Obsidian
8-66-23	Hornblende	Porphyritic Hornblende Basalt

[1] W numbers indicate localities within specific watershed areas.

[2] SL indicates localities at Stoneman Lake.

[3] Following indicate additional localities outside the specific watershed boundaries.

Alteration and Weathering.--Late deuteric alteration of the more basic minerals is quite common in the areas of the Beaver Creek watershed. Olivine is commonly the most altered mineral showing rinds and total replacements by late stage iddingsite. Most other minerals, and especially the phenocrysts, show embayments and partial dissolution by the magma after crystallization. Generally embayed and partially dissolved crystals are more prominent than fresh unaltered crystals.

The weathering effects are more clearly pronounced at the surface of flows where oxidation is enhanced by rapid temperature change and where interfaces are present between rock minerals and the oxidizing agents of the atomsphere. Weathering also is enhanced by the presence of water which usually contains dissolved organic acids. The chemical break-down of the igneous minerals of basaltic lavas yields products which are represented in the residual soils and those carried away by aqueous solutions.

Table IV gives the expected decay products of the common minerals of the Beaver Creek watershed lavas under normal weathering conditions. The normal soils should be dark in color, usually red, and have little free silica. They should be composed mainly of clays with little permeability and normally would act as impervious barriers to ground water migration unless they are intermixed with considerable rock fragments and organic debris which would make them more permeable.

Table IV

Mineral	Residual Products	Dissolved Salts
Lamprobalite	Montmorillonite, Hematite	$Ca(OH)_2$ $Mg(OH)_2$ Colloidal silica
Olivine	Hematite Magnetite	Colloidal silica and $Mg(OH)_2$ $Fe(OH)_2$
Augite	Montmorillonite, Hematite	$Ca(OH)_2$ $Mg(OH)_2$ Colloidal silica
Labradorite	Kaolinite	$Ca(OH)_2$, KOH, Colloidal silica
Andesine	Kaolinite	$Ca(OH)_2$ NaOH Colloidal silica
Magnetite	Magnetite	――――――

GEOMORPHOLOGY

General Statement.--The landforms within the part of Beaver Creek watershed treated in this report are those resulting from the processes of weathering, stream erosion, volcanic activity and diastrophism. Of these processes, the weathering activities produced the details of the topographic forms and, for the area as a whole, there are few forms attributable to weathering alone which are large enough to appear on the topographic maps. The effects of stream erosions, volcanic activity, diastrophism and the combined effects of the three factors have produced the major geomorphic development. To summarize the geomorphic evolution of this portion of the Beaver Creek watershed is to state that it is a gently sloping lava plateau surface upon which remain dissected volcanic vents and that it is in a youthful stage of dissection by slope and fracture controlled streams.

Weathering.--The effects of weathering, in which no physical transportation medium is involved, have not produced landforms large enough to show on the topographic maps but the processes of weathering do result in a mantle of dissected rock which covers most bedrock surfaces. The principal processes of weathering appear to be chemical reduction of minerals and of the available minerals olivine shows evidence of greatest susceptibility under the climatic conditions now extant. Exposed olivine crystals and masses of crystals readily combine with oxygen and water to leave an iron-rust stained cavity in the olivine-bearing rocks. The cavity becomes enlarged by the freezing and thawing water which accumulates in the cavity and, at the same time, the feldspars and remaining ferromagnesian minerals in the rock are attacked chemically by oxygen and water.

The resulting rock surface is discolored to rusty brown if the weathering products are removed as fast as they are formed or if they accumulate the weathered debris. The accumulated debris forms the basis of the variety of soils which have developed in the region and the organic matter in the soils contributes further to the chemical reduction of the bedrock.

Alternate freezing and thawing of water in any cavities which the water may enter is the most effective of the mechanical alteration agents. The rock materials separated from the parent rock range in sizes from silt and sand sizes to blocks three to four feet on a side. All of the scree produced in this manner is sharply angular and the angularity is modified by chemical weathering or by stream transportation.

Angular debris resulting from the wedgework of ice yields angular blocks of a wide range of sizes which cover gently sloping surfaces and, in addition, the flat surfaces from which the pieces were removed should show no preferred directions. The rock surfaces produced by such mechanical activity are often confused with fractures in the rock which result from other processes including lava flow structures, shrinkage and tectonic processes.

Rock slabs loosened by other methods of weathering are subject to the stress of gravity and, in answer to the stress, piles of debris accumulate at slope breaks as talus or scree. The area shows only relatively small deposits of this type which would not suggest any significant effect on the water retention capabilities; in other words, the accumulations of weathered debris are not large enough to constitute aquifers. Only one small mass, involving enough material to be considered as a landslide, occurs about ½ mile south of Stoneman Lake. The deposit appears to have deflected to a minor degree the drainage directions of two tributaries of one stream system.

The most important effects of weathering, insofar as the purposes of this report are concerned, are to produce altered materials from the parent rocks and to leave surfaces which are like the fracture surfaces. It seems obvious that the depth of weathering back of any exposed rock surface is no more than two to three feet at a maximum and it is less than that on most surfaces. The debris accumulates to greater thickness following transport and deposition below slope breaks.

Volcanic features.--Volcanic geomorphic forms are the surfaces upon which the drainage system has developed. Rising above the lava flow remnants are cones, cinder piles and volcanic vents, supported in part by resistant rocks exposed as dikes and necks, which served as the egress for gases and pyroclastic debris. The cones exhibit nearly all stages in the reduction to the general topographic elevations of the lava flows. The maximum elevation reached by any of the cones is approximately 7900 feet and the base of the cone is approximately 7300 feet resulting in a maximum local relief of about 600 feet for the constructive eruptive forms. Most of the cones attain a circular pattern whereas a few are elongate northwest to southeast only because the elongate forms tend to be composite and follow the linear trend of the fractures which control their alignment.

The vents of all stages of dissection show a definite alignment parallel to the northwest-southeast set of fractures and in this alignment, the vents show three major parallel groups. The easternmost group, as shown on the geologic map, occurs immediately east of Stoneman Lake. Composite cones and vents with minor intrusive rocks cover nearly all the fracture zones in the area of the map. Two other aligned groups of vents, none of them well developed, occur east of the highest and best developed vents.

It is apparent that the eruptive vents which now constitute the topographically high areas are late stages in the construction of the plateau surface. They cut across early stage II lava sheets and the relatively younger stage III lavas, which can be traced to the vents, rest with discordance on older lavas. The fact that the cones are built of pyroclastic material further suggests that the cones represent late stages of volcanism wherein the lava vents were nearly clogged with lava and the last remaining gas escaped with explosive force. Certainly, the earlier lavas, which spread far afield and flowed down the ancient Mogollon Rim came from unobstructed fissures.

The pyroclastic structures were built by extrusive gases and eruptive rock which cut through the older lavas and came to rest on the surface of the older lavas. The fact that the stage II lavas blanket rather evenly the plateau surface and even cascaded southwestward indicates that they were of relatively low viscosity. Presumably, the stage II lavas rose from the same fissures along which the younger cinder cones and explosive structures occur. The more fluid stage II lavas were present in copious amounts as indicated by the maximum thickness of nearly 700 feet in Wet Beaver Creek. However, the thickness decreases to zero near Apache Maid ranch where the Kaibab Formation is exposed.

Because the regional slope of the topographic surface on the stage II lavas is southwest and because the surface of that slope shows little local relief, it is apparent that the liquid rock stream flowed into and filled the lower available topographic depression to the greatest thickness. The underlying and ancient hills on the pre-lava surface are those areas where the lava cover is thinnest, as, for example, at the Kaibab outcrop near Apache Maid ranch. Consequently, the thicker lavas occur in the pre-lava valleys and, like streams of water, they moved down these valleys until the lava chilled to the solid state. Sufficient early lavas erupted to obscure, almost completely, the underlying and older drainage system.

Volcanic Control of Drainage.--The surface built by the outflow of lava sloped gently but perceptibly southwestward down and over the original Mogollon Rim and tended to decrease and obscure that steeper escarpement. Upon this lava surface a stream system grew as soon as the temperature of the rock permitted stream flow and the stream moved only in response to the initial slope. The evidence indicates an excellent example of consequent streams flowing in a subparallel drainage pattern.

The structure developed as a result of the flow patterns of the lava exerted some control on the direction taken by the streams. Also important are the tectonic fracture patterns which were very soon impressed upon the lavas as they hardened. Streams on the eastern side of the project area display a marked angular pattern and the angular pattern becomes less obvious toward the southwest where the slope control is greater.

Etching of the fracture pattern into relief provided zones of weakness which are now in the process of being occupied by subsequent streams.

Brady Canyon on the extreme east of the project area, shows especially well the fracture control on the direction of the stream. The two preferred directions of the flow in the angular stream tend to be parallel to the dominant directions of tectonic fractures. The angular pattern of the stream is lost in the downstream direction at the zone where slope control exceeds control by the etched fracture pattern.

The three sets of aligned eruptive vents force the streams which rise east of the vents to pass southward of the principal group of vents. The drainage south of the vents still belongs to the consequent stream system and the diverted group of streams contributes to the drainage through Wet Beaver Creek. Through this method and the tapping of subsurface water in the Coconino Sandstone Wet Beaver Creek has attained a degree of mastery in the area. The deeper portions of Brady Canyon through which the stream passes to reach Wet Beaver Creek, is restricted by a small group of vents and a lava flow of limited extent. Upstream from the group of vents the stream valley shows a few sharp bends and, therefore, the tectonic control of its course. The restricted passage of the lower portion of the stream and the broad, open form of the valley upstream from the canyon strongly suggest that the stream was dammed for a time by the lava flow. The present position of the stream appears to be near the western edge of the lava flow which was the lowest elevation available.

The lava flow adjacent to Brady Canyon represents viscous lava emerging from a lava lake immediately east of the canyon. The group of vents associated with the flow constitute the remnant of a large crater which was breached on the west side to allow emergence of the lava.

Collapse Features.--The remaining topographic features are relatively minor and all may be classed as collapse structures. A few small collapse structures occur in the southern part of watersheds 7, 10, and 13 and on the south edge of Brady Canyon south of watershed 12. These structures range in size from a few feet to about 300 feet in diameter. They result from flowage of lava from underneath an already frozen lava cover. The unsupported lava cover yields to weathering and gravitational stress by collapsing shortly after freezing of the lava.

The largest of the collapse structures is the depression occupied by Stoneman Lake (Plate 10). The Stoneman Lake structure is too large to be explained by collapse into a lava flow cavern. The present crater floor is nearly 300 feet below the rim and is underlain by lake beds at least 300 feet thick* indicating that the original lava roof has collapsed more than 600 feet (Plate 2). This distance exceeds the total thickness of lava believed to be present in this area. Possible explanations of this structure are collapse into a magma chamber at greater depth or into fractures or caverns in the underlying sedimentary rocks.

* Well data from Malcom Ayeres Drilling Company, Phoenix.

Stream System.--Wet Beaver Creek is the closest approach to a master consequent stream in the subparallel drainage system and it attains that status only through the stream control exerted by the aligned volcanic vents. The large number of closely spaced streams in the system with no master stream signified that the stream system is not highly advanced but, is relatively young.

The geomorphic history indicated by the features shown on Plate I suggests an original subparallel pattern developed on the early lava surface with drainage to the southwest. The group of aligned vents in the central part of the area obstructed the flow and diverted the headwaters southward to drain into Wet Beaver Creek. Subsequently a lava flow breached the west wall of the caldera east of the present Brady Canyon, to dam the south flowing stream. Eventually, sufficient water collected in the lake to overflow the lowest elevation of the dam at its western extremity and Brady Canyon was carved as the south flowing stream agained drained to Wet Beaver Creek.

The remaining southwest-flowing consequent streams west of the aligned vent systems are the beheaded remnants of consequent streams which once traversed the region. Since the time of beheading, the remnant consequent streams have grown headward to claim most of the drainage coming from the aligned vents. The observed pattern and the lack of a single master stream is characteristic of consequent slopes such as this lava covered plateau.

Structural features.--Geomorphic forms resulting directly from tectonic activity do not make an effective contribution to the topography in the immediate area of research but such forms as graben are widely dispersed in the surrounding area. Munds Park Graben and a graben south of Mormon Mountain are examples of such structures (Plate 3). The fault line scarp which parallels Lake Mary is another prominent feature of the landscape. The exposures of faults in the walls of Wet Beaver Creek Canyon strongly suggest that the lavas of the plateau streamed southwestward over a series of step faults coincident with the faulting at the edge of the Verde Valley. The series of scarps is evident in Paleozoic rock units in the walls of Wet Beaver Creek Canyon and the fact that parts of the lava cover are faulted in addition signifies that faulting and lava extrusion continued at the same time.

The indirect effects of tectonic activity are evident in the control exerted over part of the stream pattern, particularly in the eastern part of the area. The angular pattern of Brady Canyon follows rather closely the dominant tectonic fractures in the area.

STRUCTURE

Tectonic Structures.--Exposures in and adjacent to the Beaver Creek watershed yield, for the first time, evidence which leads to knowledge of the regional structural pattern. Dominating the surface structural pattern is a system of joints of tectonic origin which are best described by stating the pattern after known geographic features. One direction is the Anderson Mesa trend which means, essentially, parallel to the Anderson Mesa fault or northwest-southeast. The other direction is essentially north-south, or parallel to the Oak Creek fault. The dominant directions are aligned parallel to the scarps and graben which result from them. Where the scarps and other traces are not visible, the alignment of volcanic vents tends to follow the same directions.

A less apparent joint set subsidiary to the major joint system deviates from the Anderson Mesa trend by 10 to 15 degrees more toward the south.

Within the research area, the dominating directional trend is north 35°west or, that which is represented by the alignment of Lake Mountain-Jones Mountain, hereafter referred to as the Lake Mountain trend. The sets of joints and scarps as they appear on the air photographs in areas adjacent to the project area yield the strongest evidence of the Anderson Mesa or Lake Mountain trend. Discontinuous fractures which appear in many cases to control an alignment of vegetation patterns are good indicators of the joints. In addition to control of vegetation patterns, other fractures show tonal differences and, in the eastern part of the area, scarps, graben and drainage patterns suggest the trends. There are no instances in which a single joint of the Anderson Mesa or Lake Mountain trend can be traced for more than a few hundred feet.

Exposures of both major tectonic joint sets occur in several areas surrounding the immediate research area. Large joint surfaces within the walls of Wet Beaver Creek Canyon, in addition to the fault surfaces in the same area, clearly display the preferred joint directions. South and east of Wet Beaver Creek to Clear Creek is a large area with no lava cover where the sedimentary rocks are cleaved parallel to the two dominant directional trends (Plate 11). Between Mormon Mountain and Lake Mary is another area with no lava cover and the two dominant joint sets plus the subsidiary set are deeply etched in The Kaibab Formation. It is from these surrounding areas that the tectonic fracture pattern may be followed under and into the lava cover of the Beaver Creek watershed.

The evidence suggests that the two dominant directions of faulting are presistent enough within the Beaver Creek watershed to constitute a part of the regional structure. The features cited within the Beaver Creek watershed show the trends and localities affected by the joint system. Differential movement between blocks is not easily detected and the fact that features indicating the fracture trends occur in groups would suggest that little if any differential movement has occurred between blocks on the plateau. For the purposes of this work it is significant to note that the fractures cut the lava cover as well as the underlying sedimentary rocks units, and that the evidence further suggests that the tectonic joint system is a major entry for water into the subsurface.

Volcanic Flow Structures.--An additional set of fractures is interpreted from the relation of lava flows and fractures of limited extent which follow flow margins and indicate stresses within the flows. Such fractures are best read from air photographs on which vegetation patterns, tonal differences and lava flow trends, appear together. The air photographs available for this study permit only an indication of the joints of this type because of the granularity of the photographs, but additional joints and other flow structures are readily exposed to field study in several limited areas.

At linear intervals of approximately 6 inches to four feet on the exposed sides of some flows are joint cracks not related directly to stress distribution within the active flow and which show a random directional distribution. Many cracks of this type are open at the surface and extend downward for several feet at a maximum in a given flow. The wide and irregular intervals between such cracks and their random distribution suggest, tentatively, that this group may result from shrinkage attendant upon cooling.

SUMMARY OF GEOLOGIC HISTORY

The sequence of events in the geologic history of this area may be summarized as follows:

A. Pre-Cenozoic History--Deposition of sedimentary rocks intermittently during the Paleozoic and Mesozoic Eras as cited in other references to the Mogollon Rim region (l.e. Twenter and Metzger, 1963).

B. Cenozoic Era--

1. Uplift and erosion which removed nearly all the Mesozoic sediments. Possible initiation of the regional fracture system.
2. Pre-volcanic faulting along high-angle faults in the Mogollon Rim region. At least 100 feet of movement occurred in the faults displayed in Wet Beaver Creek Canyon.
3. Volcanism--Stage I ash beds and volcanic breccia, probably beginning in Miocene time. Disruption of the older drainage system.
4. Recurrent movement on high-angle faults.
5. Volcanism--Stage II lava flows and some ash falls.
6. Recurrent movement on high-angle faults during and following the volcanic activity.
7. Initiation of southwestward drainage system on the volcanics.
8. Volcanism--cinder cones and associated flows, local disruption of drainage.
9. Establishment of present drainage, continuation of canyon cutting.

SUMMARY OF FACTORS AFFECTING RUNOFF

Slope.--The slope of the plateau surface on the step-fault system of the ancient Mogollon Rim developed as a result of the outpouring of successive lava sheets which are inclined toward the Verde Valley like the shingles on a roof. The slope controlled distribution of streams has yielded a subparallel drainage system of numerous, closely spaced streams and, because of this fact, ready access is provided for surface water to any available passages leading to the subsurface.

Rock Type.--Of the rock types exposed in the study area the basaltic and andesitic lavas are the least porous and permeable. Where not fractured they are essentially imprevious and shed water readily. The cinder deposits are highly porous and are permeable even where cemented. Water falling on the cinder cones may be expected to percolate downward with very little run off. However, because the cones are built upon a lava base the nature of the underlying lava determines whether the water continues downward to the regional water table or seeps out as springs along the base of the pyroclastic material. The bedded pyroclastic material between lava flows is porous and probably stores some downward percolating water or conducts it laterally to surface openings.

The Paleozoic sedimentary rocks previously described are both porous and permeable owing to their original porous nature and the abundant fracture systems developed within them. Thus any seepage water which gets through the volcanic cover may be expected to continue downward through the sedimentary beds to the water table.

Structure.--The regional fracture system in the area affects all the rock units in the stratigraphic column and, therefore, this system provides openings through which surface waters may percolate downward to the subsurface aquifers. Volcanic eruptive processes utilized the same regional fractures with the result that some parts of the regional system are closed, but the wide distribution of closely spaced fractures offers ready opportunity for seepage of water downward. Fractures associated with the flow and shrinkage of lavas yield additional openings for water seepage. Water held in such fractures may not find its way into the subsurface immediately. It may be held in storage and some eventually may seep into the deeper subsurface or find access to the surface through springs.

The regional fold pattern affects the movement of subsurface water. Twenter and Metzger (1963) and Rush (1965) have demonstrated that the subsurface water gradient is wouthward and westward toward the deeper valleys of Wet Beaver Creek and the Verde Valley.

Weathering.--The fractures due to weathering processes create a mantle over parts of the exposed rock but the cracks which result from the process may not be expected to lead into subsurface aquifers. The volumes of weathered material on the land surface in the area do not appear to be large enough to contain appreciable amounts of water although such material is porous and permeable.

The clayey soils developed on the lavas and cinders may be expected to provide a seal to downward percolation of water locally, but over much of the area this soil cover appears too thin or discontinuous to be significant. Buried soils between lava flows may also serve locally to divert downward percolating water laterally.

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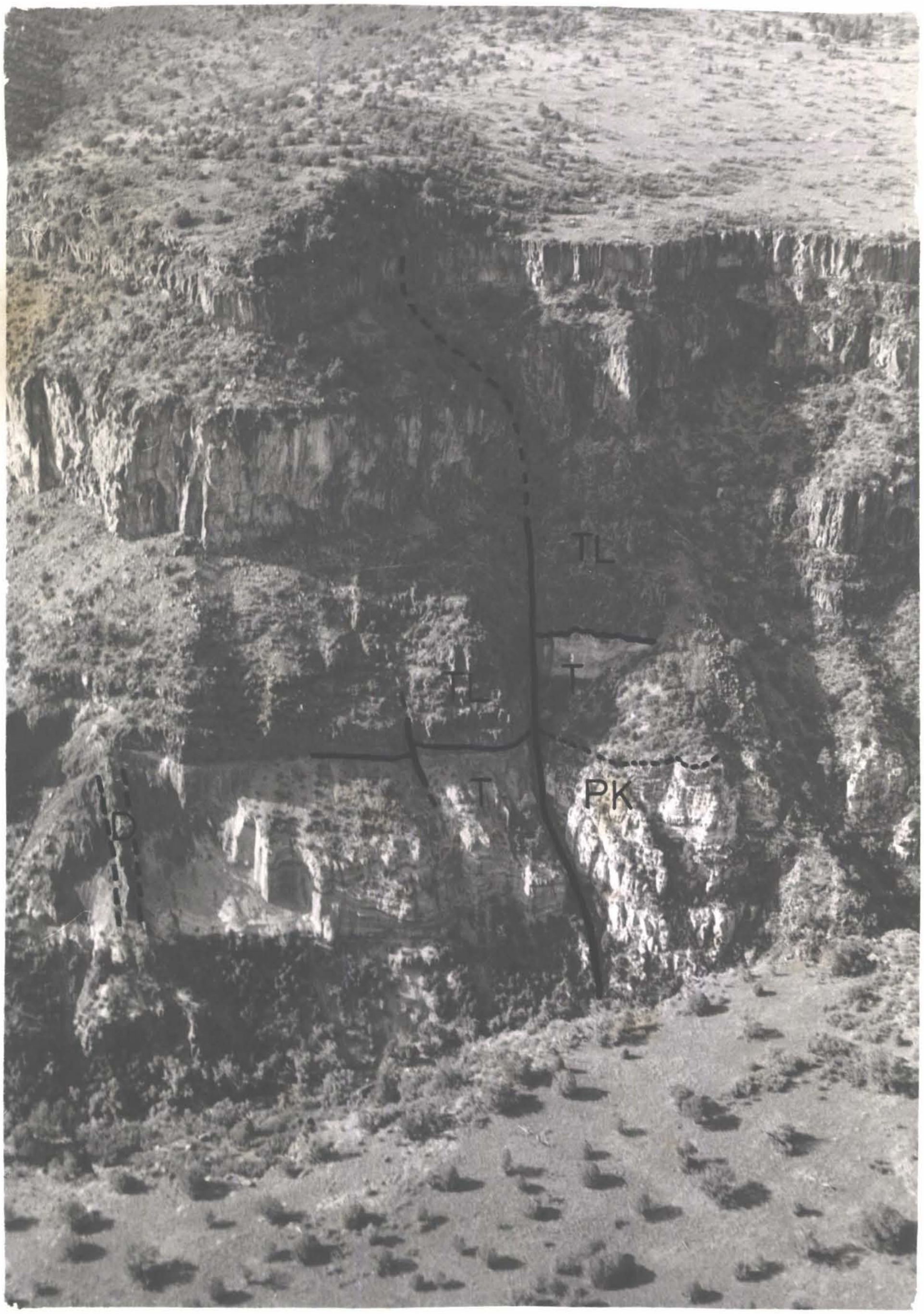


Plate 5. Air view of measured section and major high-angle fault on north wall of Wet Beaver Creek Canyon, three miles south of Apache Maid Mountain. Kiabab Formation, Pk; tuff, T. lava flows, TL, dike, D. Stratigraphic separation along fault is approximately 250 feet for the Kiabab, 100 feet for the tuff beds, 30-40 feet for the intermediate flows and 0 to 5 feet for the uppermost flows.

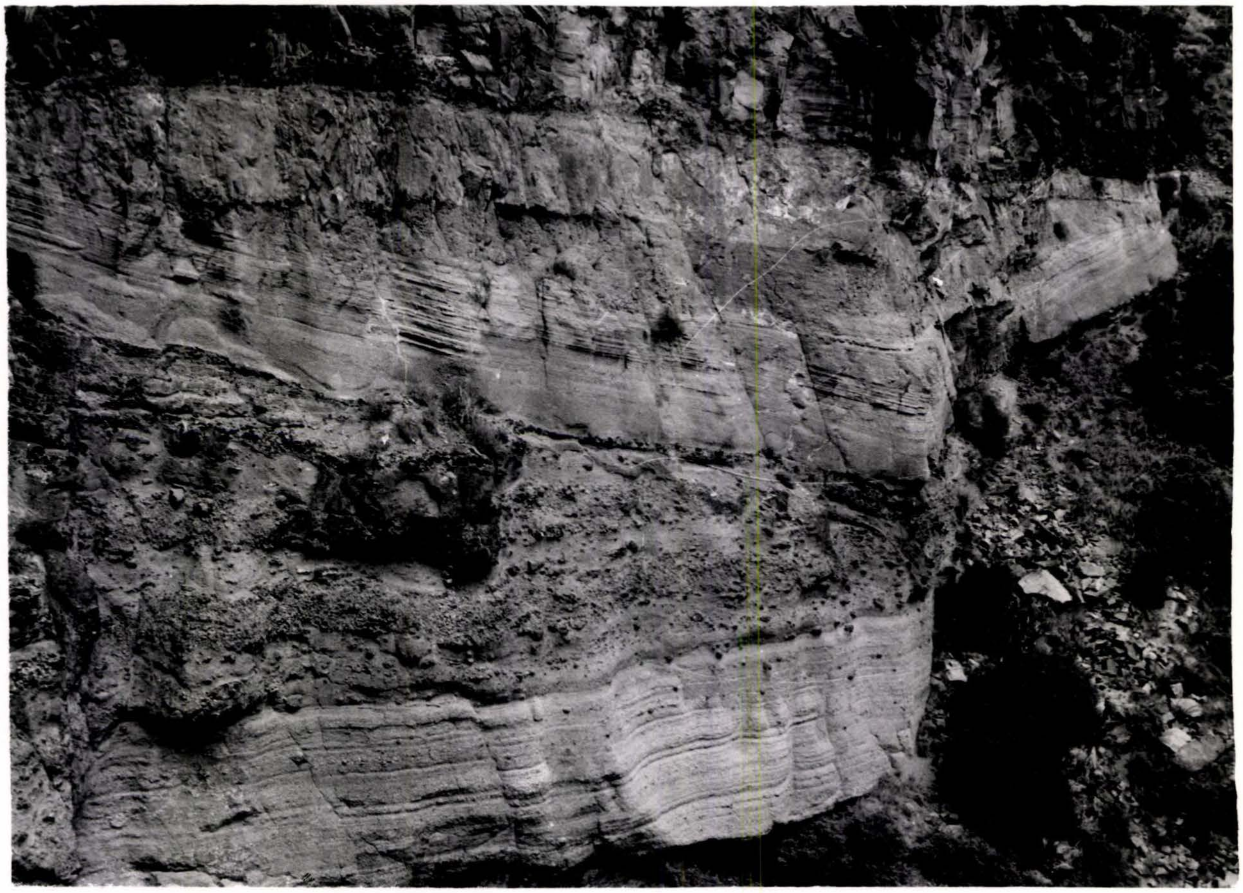


Plate 6. Close-up view of tuff beds and showing also the base of lowest lava flow, Wet Beaver Creek Canyon.

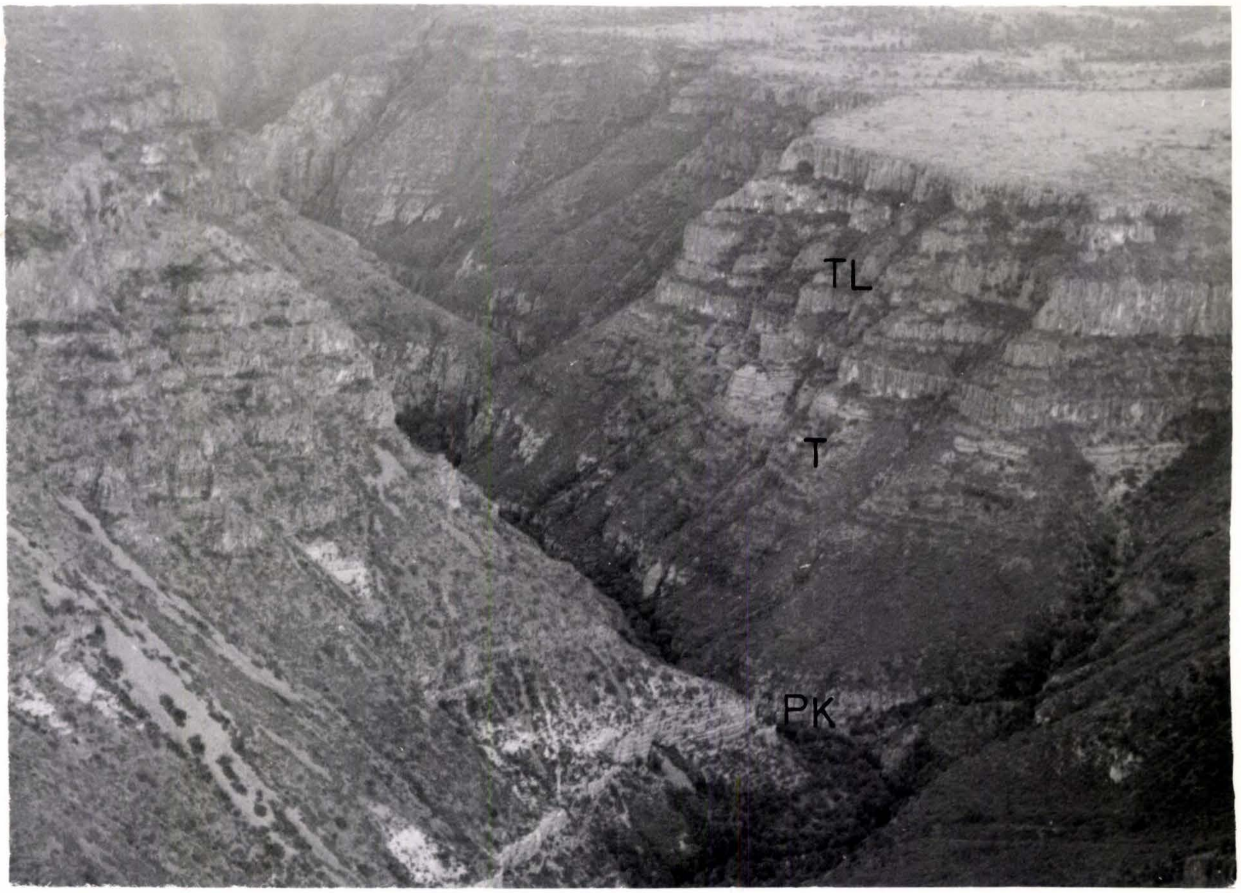


Plate 7. Aerial view of flows in upper Wet Beaver Creek Canyon Kiabab formation; PK, tuff beds, T. lava flows, TL.

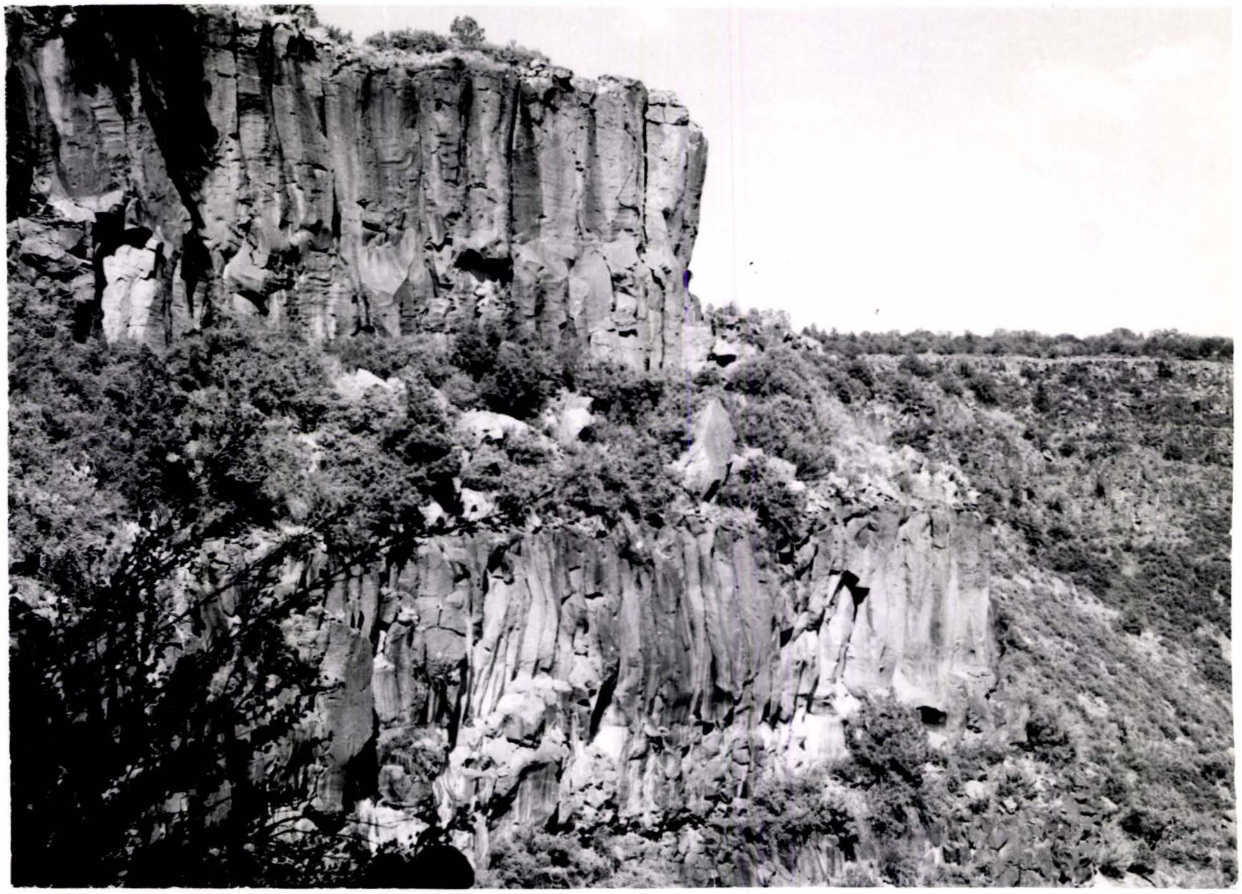


Plate 8. Columnor Jointing displayed in two uppermost massive flows,
Wet Beaver Creek.

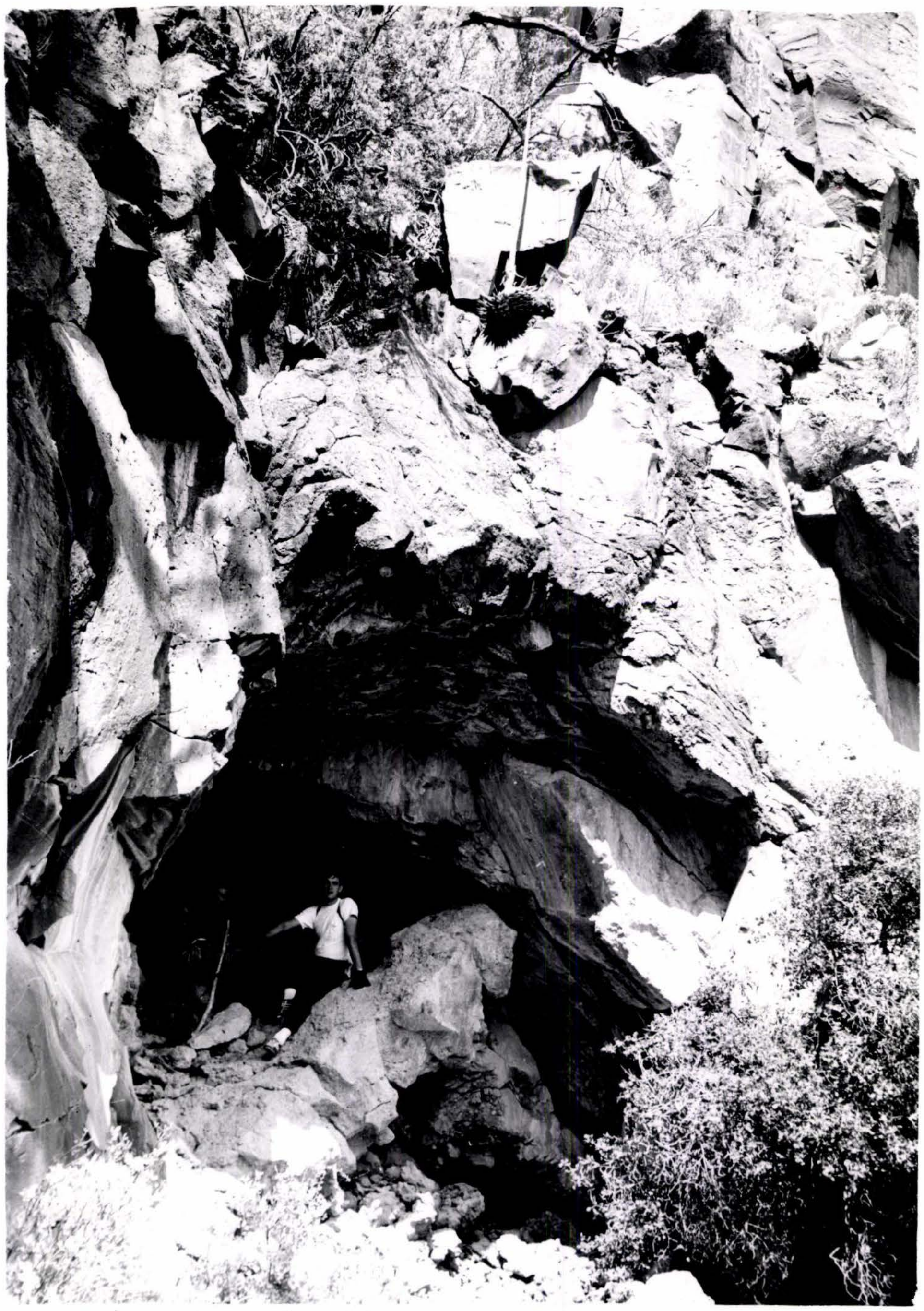


Plate 9. Lava tunnel near base of a massive 120-foot flow, Wet Beaver Creek Canyon.

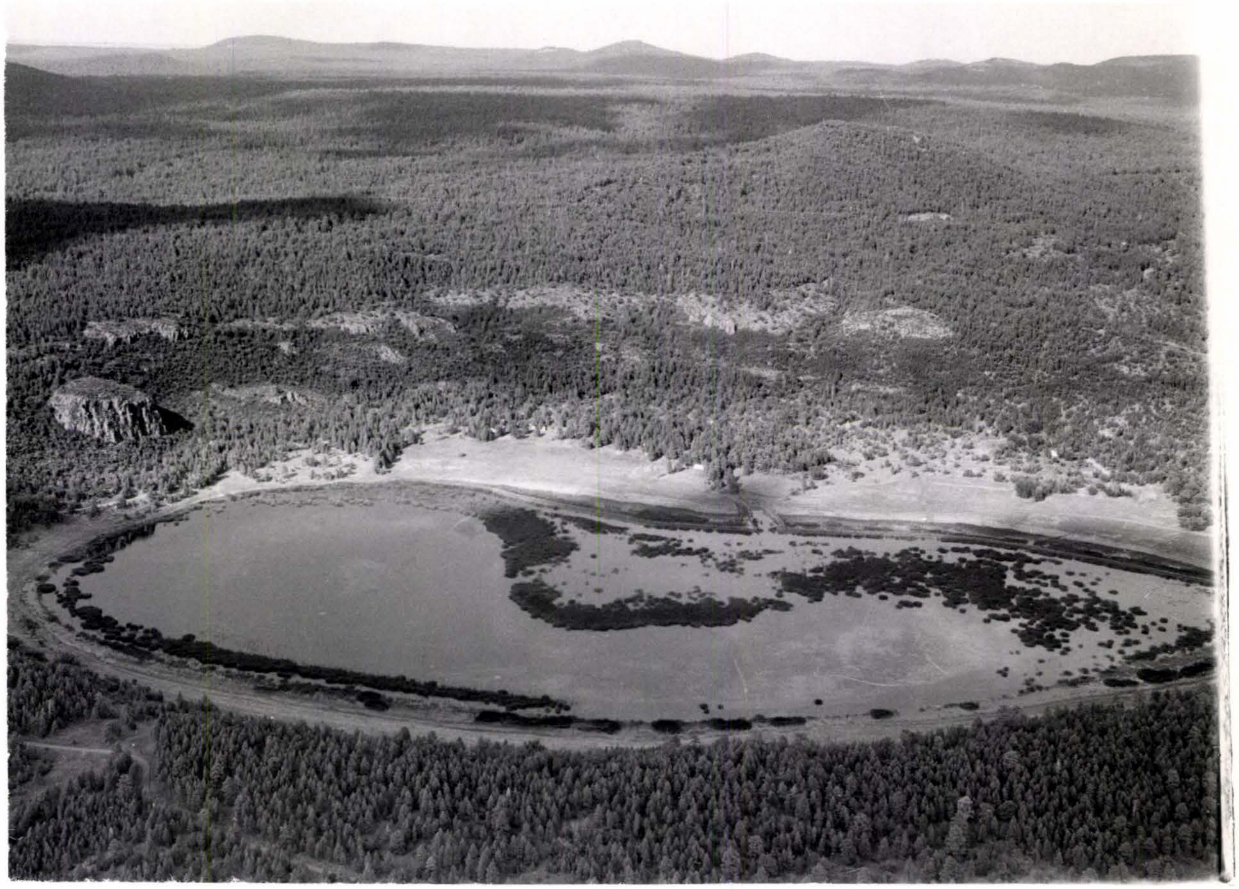


Plate 10. Aerial view of Stoneman Lake. Volcanic plug at left center.
Lake Mountain at upper right.

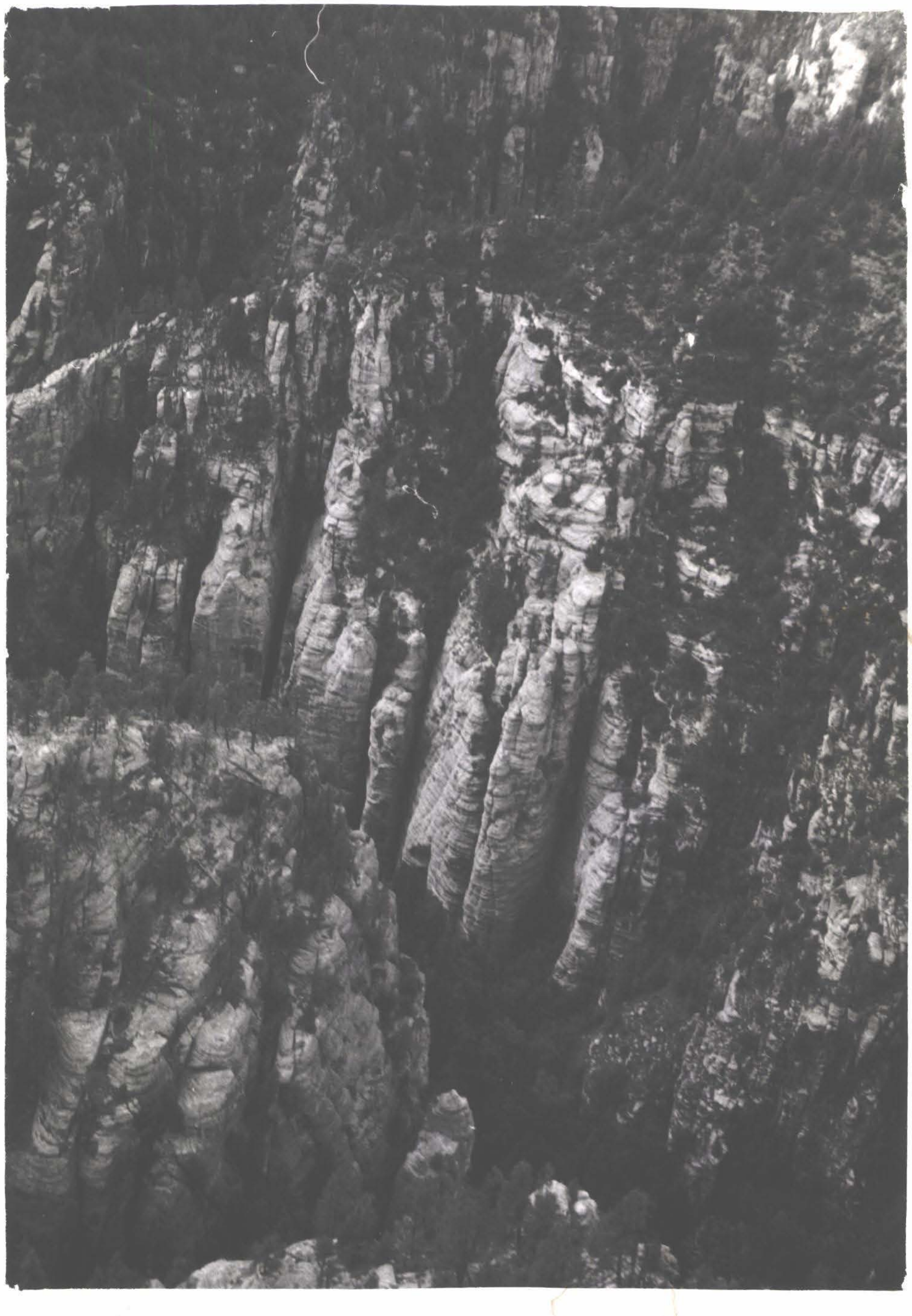


Plate 11. Northwest-trending regional fracture pattern displayed in the Coconino Sandstone at West Clear Creek

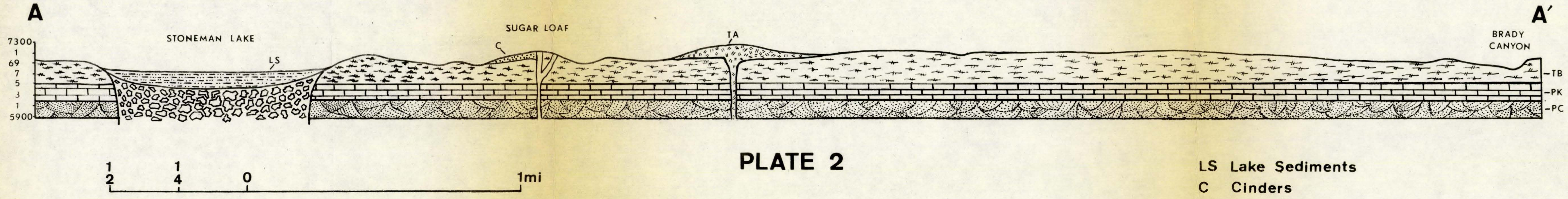
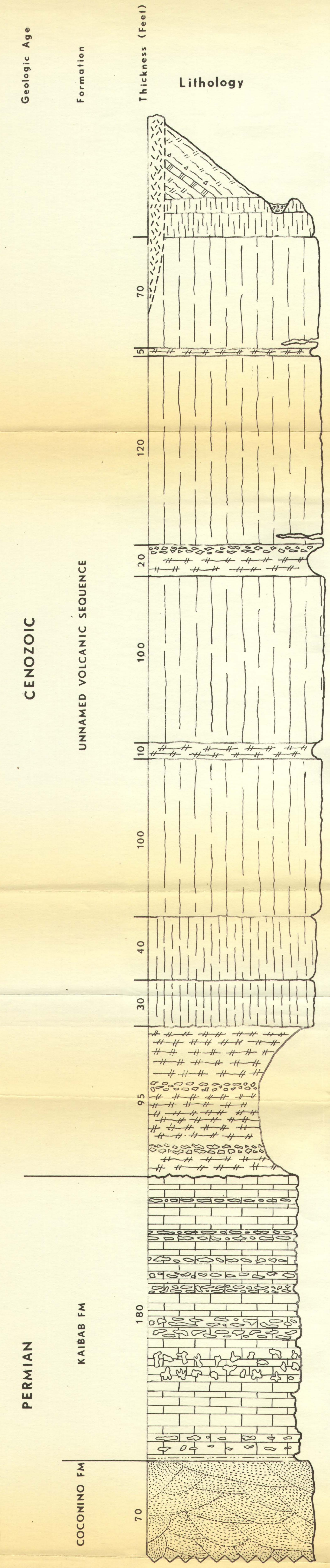

A
A′
7300
1
69
7
5
3
1
5900
STONEMAN LAKE
LS
SUGAR LOAF
C
TA
BRADY CANYON
TB
PK
PC
$\frac{1}{2}$
$\frac{1}{4}$
0
1mi

PLATE 2

GEOLOGIC CROSS-SECTION

	LS	Lake Sediments
	C	Cinders
Tertiary	TA	Andesite
	TB	Basalt
Permian	PK	kaibab
	PC	Coconino


Geologic Age
Formation
Thickness (Feet)
Lithology
CENOZOIC
UNNAMED VOLCANIC SEQUENCE
PERMIAN
KAIBAB FM
COCONINO FM
70
5
120
20
100
10
100
40
30
95
180
70

Description

CINDER CONES OF ASH AND SCORIA, PARTLY CEMENTED; COMPOSITE CONES OF INTERBEDDED ASH AND LAVA; SOME RISE 600 FEET ABOVE THE SURFACE OF OLDER BASALTS; NUMEROUS DIKES AND PLUGS.

YOUNGER BASALT AND ANDESITE FLOWS THAT CAN BE TRACED TO SOME EXISTING VENT; CONTAIN SOME COLLAPSE FEATURES.

OLDER BASALTS; MASSIVE, RELATIVELY FLAT-LYING, MOSTLY OLIVINE BASALTS; 30-120 FEET THICK; COLUMNAR JOINTING AND WEATHERING FRACTURES COMMON; SOME TUFF AND TUFF BRECCIA BEDS AT BASE OF FLOWS; LAVA TUNNELS OCCUR NEAR THE BASE OF TWO FLOWS.

THIN TO MEDIUM BEDDED TUFF, TUFF BRECCIA AND AGGLOMERATE, MOSTLY WEAKLY CEMENTED AND POROUS.

CHERTY AND SILTY-SANDY LIMESTONE, THIN BEDDED TO THICK BEDDED, SOME ONE TO TWO-FOOT BEDS OF FRACTURED CHERT, FINE GRAINED BROWN SANDSTONE AT BASE; VERTICAL FRACTURES THROUGHOUT AND IN SOME PLACES HAVING SOLUTION CAVERNS AND CHANNELS.

CALCAREOUS QUARTZ SANDSTONE; WELL SORTED AND SUBROUNDED GRAINS, 95% QUARTZ; CALCITE OR IRON OXIDE CEMENT; EOLIAN CROSS BEDDING THROUGHOUT POROUS AND PERMEABLE.

PLATE 4

COMPOSITE COLUMNAR SECTION

WET BEAVER CREEK

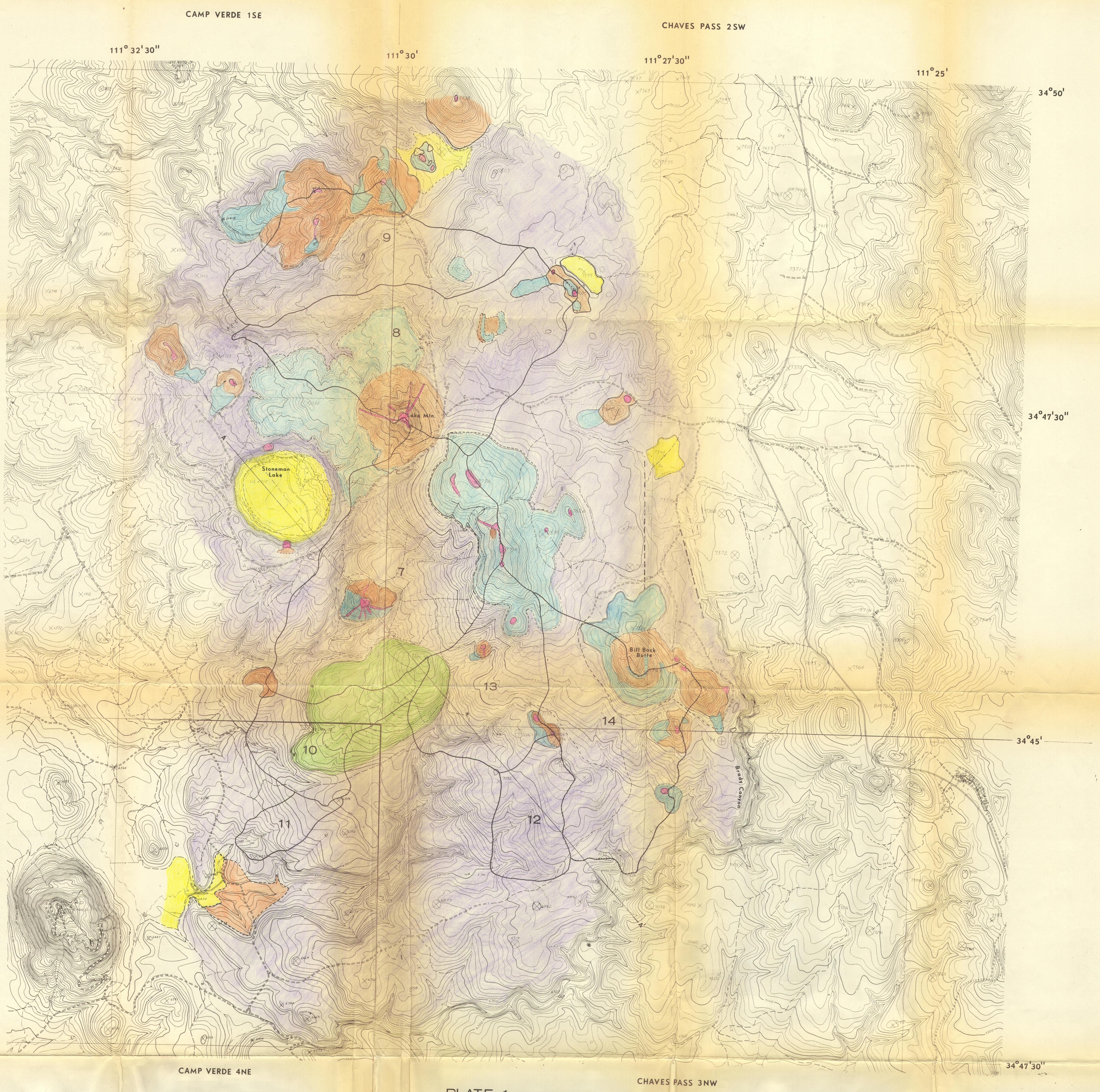

CAMP VERDE 1SE
CHAVES PASS 2SW
111° 32'30"
111°30'
111°27'30"
111°25'
34°50'
34°47'30"
34°45'
9
8
Lake Mtn.
Stoneman Lake
A
7
Bill Back Butte
13
14
10
11
12
Brady Canyon
CAMP VERDE 4NE
CHAVES PASS 3NW
34°47'30"

PLATE 1

GEOLOGIC MAP

PART OF THE BEAVER CREEK WATERSHED AREA,
COCONINO COUNTY, ARIZONA

~ WATERSHED BOUNDARY

7–14 WATERSHED NUMBERS

0 ½ 1 2 miles

Scale: 3.2 inches equal 1 mile

Prepared by:
Stanley Beus
Richard Rush
DeForrest Smouse

↑ North

🟨	ALLUVIUM AND LAKE BEDS
🟫	CINDERS
🟦	YOUNGER BASALTS
🟩	ANDESITE
🟪	OLDER BASALTS
🟥	INTRUSIVE – DIKES AND PLUGS
🟧	KAIBAB FORMATION
—----	CONTACT–DASHED WHERE APPROXIMATELY LOCATED
—--	FAULT – DASHED WHERE APPROXIMATELY LOCATED
—·—·—	FRACTURES
*	COLLAPSE FEATURES

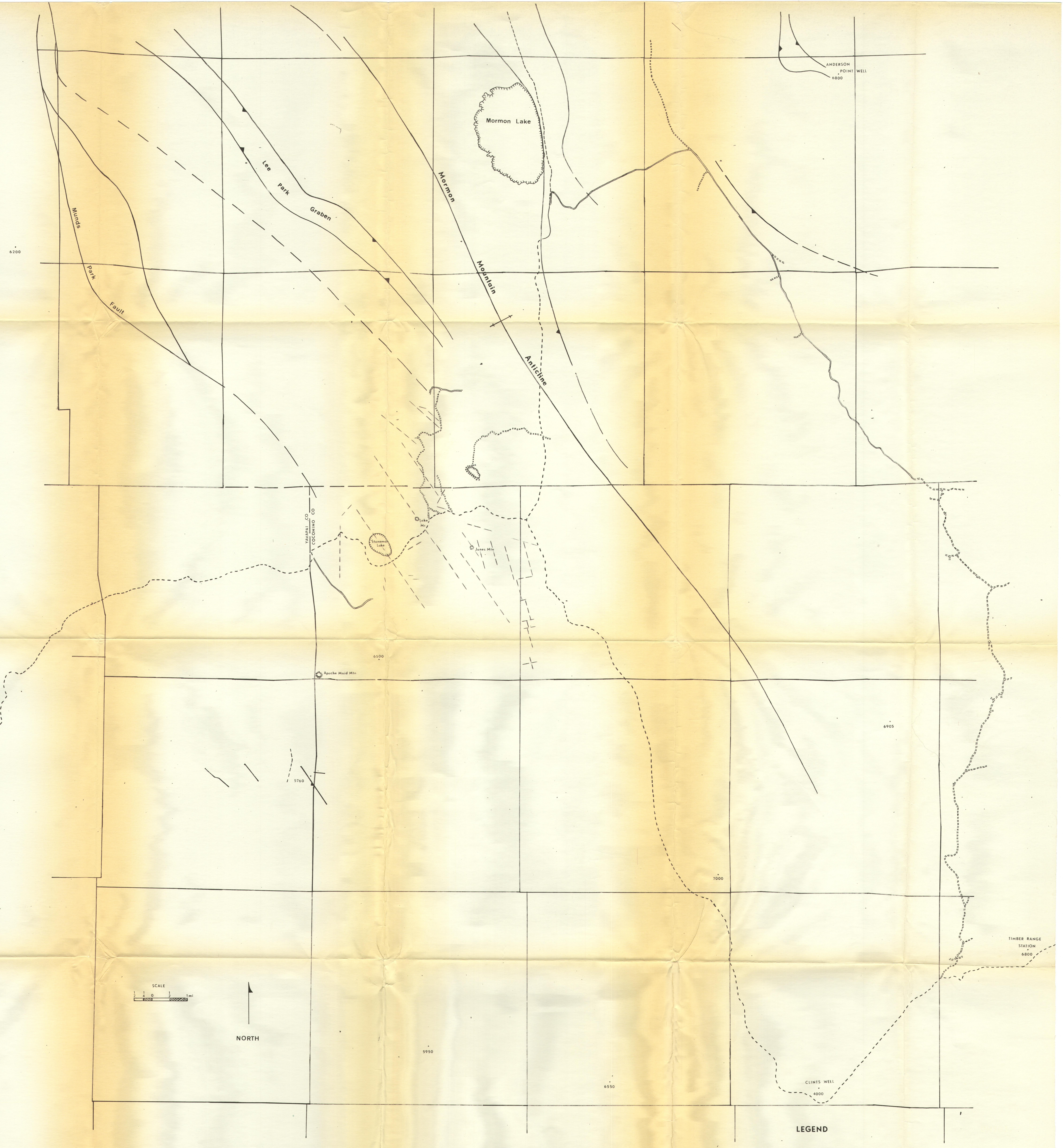

ANDERSON POINT WELL
6800
Mormon Lake
Lee Park Graben
Mormon Mountain Anticline
Munds Park Fault
6200
YAVAPAI CO
COCONINO CO
Lake Mtn
Stoneman Lake
Jones Mtn
6500
Apache Maid Mtn
5760
6905
7000
TIMBER RANGE STATION
6800
SCALE
1/2 1/4 0 1/2 1 mi
NORTH
5950
6550
CLINTS WELL
4000

PLATE 3

GEOLOGIC STRUCTURES

IN THE BEAVER CREEK AREA

LEGEND

Anticline Axis

Joints

Roads

Faults—triangle on downthrown side

Elevation of the top of the Kaibab Formation

4350